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RADIATION AUGMENTED COMBUSTION

A. E. CERKANOWICZ
CORPORATE RESEARCH LABORATORIES
EXXON RESEARCH AND ENGINEERING COMPANY
LINDEN, NEW JERSEY 07036

391338 S/C

JULY 1979

INTERIM REPORT AFOSR-TR-79-
CONTRACT NUMBER F49620-77-C-0085

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Enhanced Combustion	Excited State Kinetics
Unsensitized Ignition	Flame Propagation
Vacuum Ultraviolet Radiation	Spark Ignition
Ultraviolet Radiation	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediary species are being investigated. Pulsed VUV (vacuum ultraviolet) light sources and continuous UV (ultraviolet) light sources are being used for this purpose. Experimental efforts are directed at elucidation of light source conversion efficiency and spectral characteristics, and reactant mixture-photon interactions. A complementary effort involves the development of analytical capability required for modeling photochemical initiation and enhancement of combustion.

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TABLE OF CONTENTS

	Page
ABSTRACT	i
STATEMENT OF WORK	1
STATUS OF RESEARCH EFFORT	4
REFERENCES	12
PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT	13
INTERACTIONS/OUTSIDE INTEREST	14
POTENTIAL APPLICATION OF RESEARCH RESULTS	15
ATTACHMENT I - UV COMBUSTOR LIGHT SOURCE DEVELOPMENT FINAL REPORT	16
ATTACHMENT II - RADIATIVE AUGMENTATION OF COMBUSTION CONTRACT F49620-77-C-0085	26

ABSTRACT

Radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediate species are being investigated. Pulsed VUV (vacuum ultraviolet) and continuous UV (ultraviolet) light sources are being used for this purpose. Experimental efforts are directed at examining light source efficiency and spectral characteristics, and reactant mixture-photon interactions. A complementary effort involves the development of analytical capability required for modeling photochemical initiation and enhancement of combustion.

This document represents a brief communication which reviews the progress of research since the first annual report (May 31, 1978 thru May 31, 1979). The work was performed at Exxon Research and Engineering Company, Linden, New Jersey with Dr. A. E. Cerkanowicz as Principal Investigator. Within Exxon, the work is carried out in the Corporate Research-Technology Feasibility Center, Contract Research Division, Combustion Science Area. A full technical report which details the program effort up to this point is in preparation.

Ignition and combustion tests have been performed on propane-air mixtures for the first time. Radiative combustion initiation experiments and spectrographic data have been obtained which characterize light source intensity as a function of wavelength, pulse time, and spatial location. This information is being used to improve our computer model of the radiative ignition process and to define new light source requirements for practical combustor applications. The computer model has been advanced and has been successfully used to formulate a new mechanism for radiative enhancement of combustion.

STATEMENT OF WORK

The current program work statement is presented below for the effort covering the period June 1977 thru November 1980 and a revised program milestone chart is provided in Figure 1:

The contractor shall furnish scientific effort during the period, together with all related services, facilities, supplies and materials, needed to conduct the following research:

a. Identify, acquire and evaluate appropriate vacuum ultraviolet and ultraviolet light sources. Purchase of available and specially modified sources will be pursued under subcontract. Source requirements will be specified based on previously determined photochemical combustion requirements. (AFOSR contract F44620-70-C-0051 and AFAPL contract F33615-73-C-2063).

b. Select and characterize radiant sources for program use. Spectrographic measurements will be employed to determine wavelength dependence of source energy output as a function of energy input and pulse duration. Pulsed sources will be evaluated in the 145-185 nm range and continuous source will be evaluated in the 200-360 nm range. Combustion initiation tests using static mixtures will also be performed to further characterize the source radiant beam.

c. Initiate experimental tests to identify and investigate the details of radiant beam-reactant mixture interaction. Explore the effects of inerts, fuel-free air zones, and depth of radiation penetration on the photo-combustion processes using gaseous, stationary reactant mixtures. Also design and initiate plug flow combustor experiments to provide for characterization of radiative effects in flowing reactive mixtures.

d. Carry out a comprehensive technical analysis to complement the experimental program. The detailed aspects of radiation-combustion interaction which lead to ignition and combustion enhancement will be considered. A consistent experimental and theoretical description of combustion augmentation will be developed.

e. Extend experimental tests on gaseous, stationary reactant mixtures to include investigation of the effect of radiant energy on the ignition and flame propagation of spark ignited mixtures. Attempt to obtain ignition using a focused, continuous light source.

f. Employ plug flow combustor experiments to investigate ignition and flame attachment in flowing reactive mixtures subjected to pulsed vacuum ultraviolet sources. Also study flame stabilization by continuous ultraviolet irradiation.

g. Design and initiate cannular combustion experiments to provide for characterization of radiative effects in non-premixed flowing reactive mixtures.

h. Utilize the experimental data and computer model to develop a consistent description of radiative augmentation processes. Undertake model revisions and refinements as necessary.

i. Perform cannular combustor experiments to investigate ignition and flame attachment in flowing, liquid-fuel, unpremixed, reactant systems subjected to pulsed vacuum ultraviolet and continuous ultraviolet irradiation.

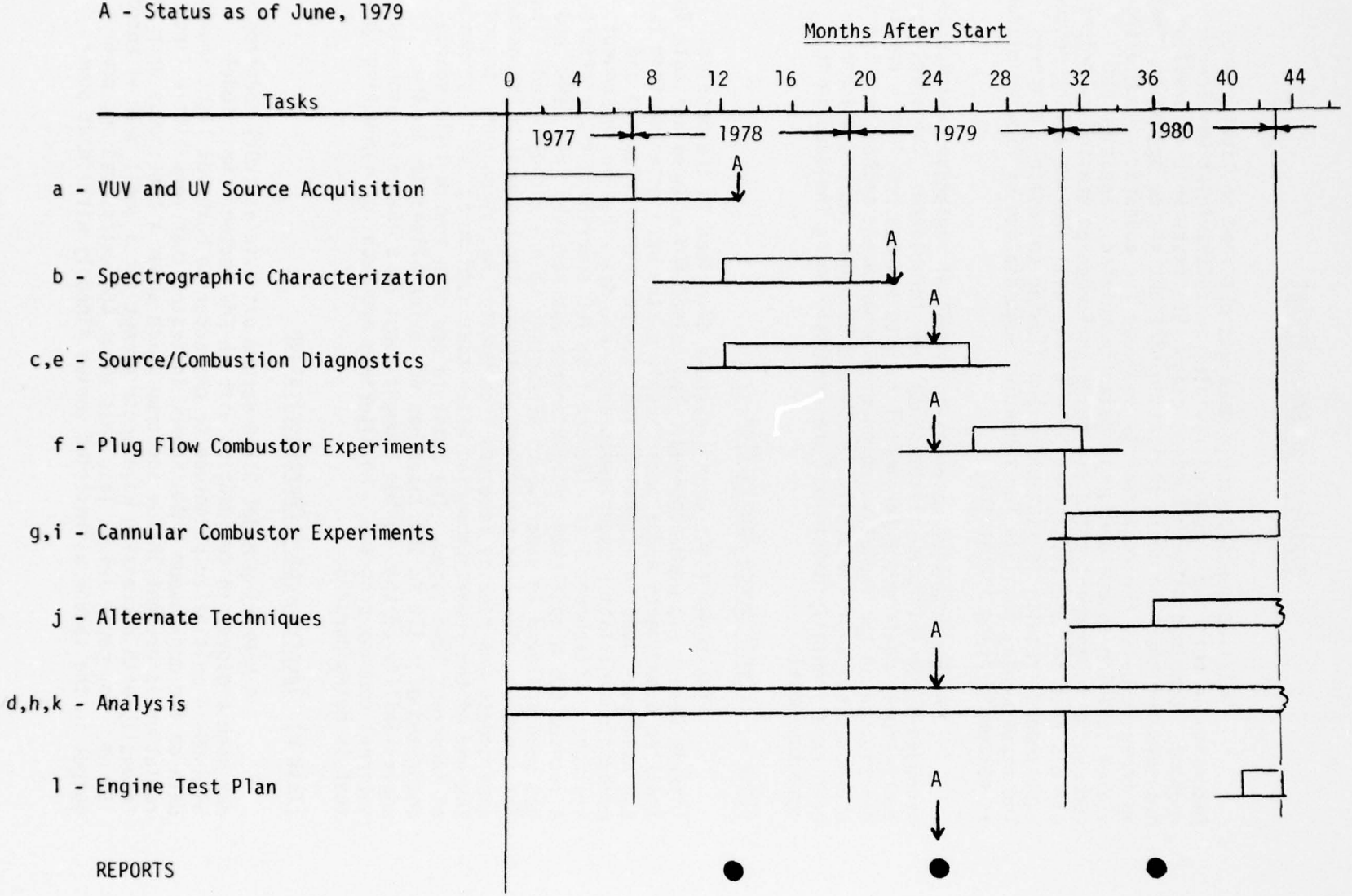
j. Identify and evaluate alternate combustion augmentation techniques for application in practical combustion hardware. Carry out simple, preliminary experimental tests of the most promising techniques as appropriate.

k. Expand the radiative enhancement model to include methane-fueled system kinetics. Perform additional analysis to parametrically characterize radiative enhancement and to assess application feasibility.

l. Develop a comprehensive test plan for larger scale engine tests of the radiative augmentation techniques, including a parametric test matrix.

FIGURE 1

PROGRAM MILESTONE REVISED (6/1/79)



STATUS OF RESEARCH EFFORT

Detailed spectrographic data was obtained on light source intensity in both the vacuum ultraviolet and ultraviolet wavelength regions. Combined with combustion diagnostic tests this information provides for thorough characterization of light source operation. Based on these results, the requirements and need for advanced vacuum ultraviolet ignition source design is being formulated. Ignition and combustion enhancement tests are being performed on stationary propane-air mixtures for the first time. This data will provide a link between experimental results in stationary and flowing combustible mixtures. The experimental facility for radiative augmentation of flowing mixtures is currently being fabricated.

A comprehensive mathematical model of radiative ignition of hydrogen-oxygen-nitrogen mixtures has been formulated. The model has successfully confirmed experimental results and has provided a revised description of the radiative combustion enhancement mechanism. Specific characteristics of the available VUV and UV light sources which have been experimentally determined are currently being included in the computer model.

(Task a) Light Source Acquisition

The three light source systems described in the previous Interim Report (1) were acquired. Ten pulsed VUV sources suitable for ignition experiments and a power supply system were received from ILC and have been used in extensive light source characterization and combustion initiation experiments which are described in subsequent sections. Attachment I is a report from ILC describing their effort. A focused 500 W continuous VUV/UV source was received from EIMAC and has been employed in experiments attempting to use steady irradiation for ignition. The 1 kW continuous UV source for combustion enhancement experiments was finally received from Optical Radiation Corp. toward the end of the reporting period after continued delay due to shipment of incorrect lamp types. The possible use of a fourth light source comprised of a 172 nm VUV laser has not materialized due to the unavailability of this system brought about by a change in emphasis of internal company programs. An alternate approach for conducting this test is being pursued.

(Task b) Spectrographic Characterization

A McPherson Model 216.5 vacuum ultraviolet (VUV) spectrograph has been employed in conjunction with an EMR Photoelectric Model 541N-09-14 multiplier phototube to characterize both VUV light sources. Data on the continuous EIMAC source indicates that very little line radiation is present in the spectrum which shows a continuous drop in intensity with decreasing wavelength except for a small peak at about 165 nm. For power levels less than about 400 watts, radiant power output in the vacuum ultraviolet varies linearly with input power.

The spectral distribution of intensity for the pulsed vacuum ultraviolet light sources supplied by ILC has pronounced peaks in the 145 to 175 nm wavelength region. This is a region of photon energy which is extremely effective in initiating combustion reactions. Thus, the spectral data clearly supports the unique ability of these light sources in radiative ignition applications. The experimentally measured pulsed VUV source intensity spectrum is shown in Figure 2. Such detailed spectral information is critical in correctly modeling the influence of VUV photons on the chemical kinetics of interest. Equally important is the pulse shape (intensity vs time) behavior of the photon flux. Although the pulse shape was found to vary with wavelength, the time integrated value (energy deposition vs time) could be correlated by assuming a pulse shape which corresponds to a classical critically damped discharge. Figure 3 shows a comparison between measured and analytically modeled pulse shapes for wavelength regions at 143.5, 146.5, 166.5, and 177.5 nm. The time dependence for a critically damped pulse is represented as follows:

$$I \sim (t/t^*) \exp (1-t/t^*)$$

where I = pulse intensity
t = time
t^* = time to peak intensity

For the pulsed VUV sources the value of t^* for data correlation was found to be essentially independent of wavelength for specific wavelength regions as follows: $t^* = 58 \pm 3$ μs for 140-223 nm and $t^* = 45 \pm 3$ μs for 223-250 nm.

Above input energies of about 6 J the pulse became undamped. As a result, the time required for total energy input increased considerably and the input energy conversion efficiency decreased. Consequently, data interpretation and comparison with single pulse inputs becomes difficult. Continued need of energy levels that result in undamped discharge will necessitate redesign of the discharge circuitry.

(Task c) Source/Combustion Diagnostics-I

A series of ignition tests were performed with stoichiometric hydrogen-oxygen mixtures. Using a reference condition of 40 kPa (300 torr) pressure, a minimum stored energy requirement for ignition using the pulsed VUV sources was determined to be about 500 mJ. This is in agreement with previous results for sources of the same generic design which indicated minimum ignition energies on the order of 250 mJ.

By using a combination of multiple sapphire windows (up to three), various air gaps between two windows, and various window opening diameters, a measure of the degree of VUV beam spreading was obtained. Although this data has only been reduced on a preliminary basis, it indicates that the pulsed VUV source can be considered as a point source located between the central electrode and rear window surface. As a result, extensive beam spreading occurs and penetration of fuel-free boundary layers (even if oxygen free) will require a substantial energy increase. Based on these preliminary results, the estimated energy increase required to achieve radiative ignition with

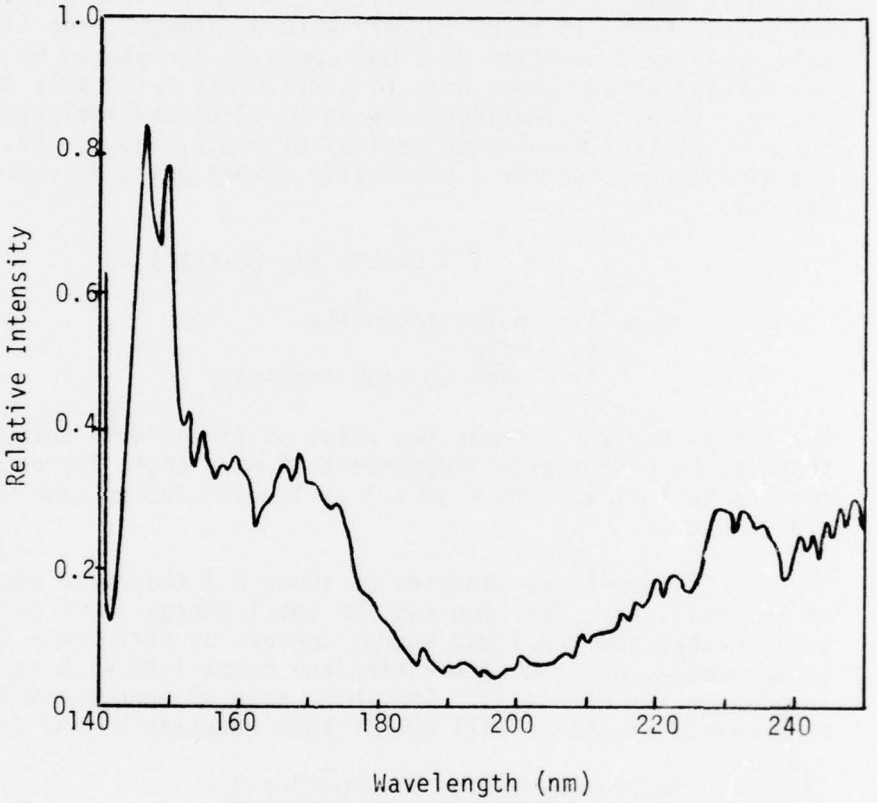


Figure 2 - Spectral Distribution of Intensity
for Pulsed VUV Light Source

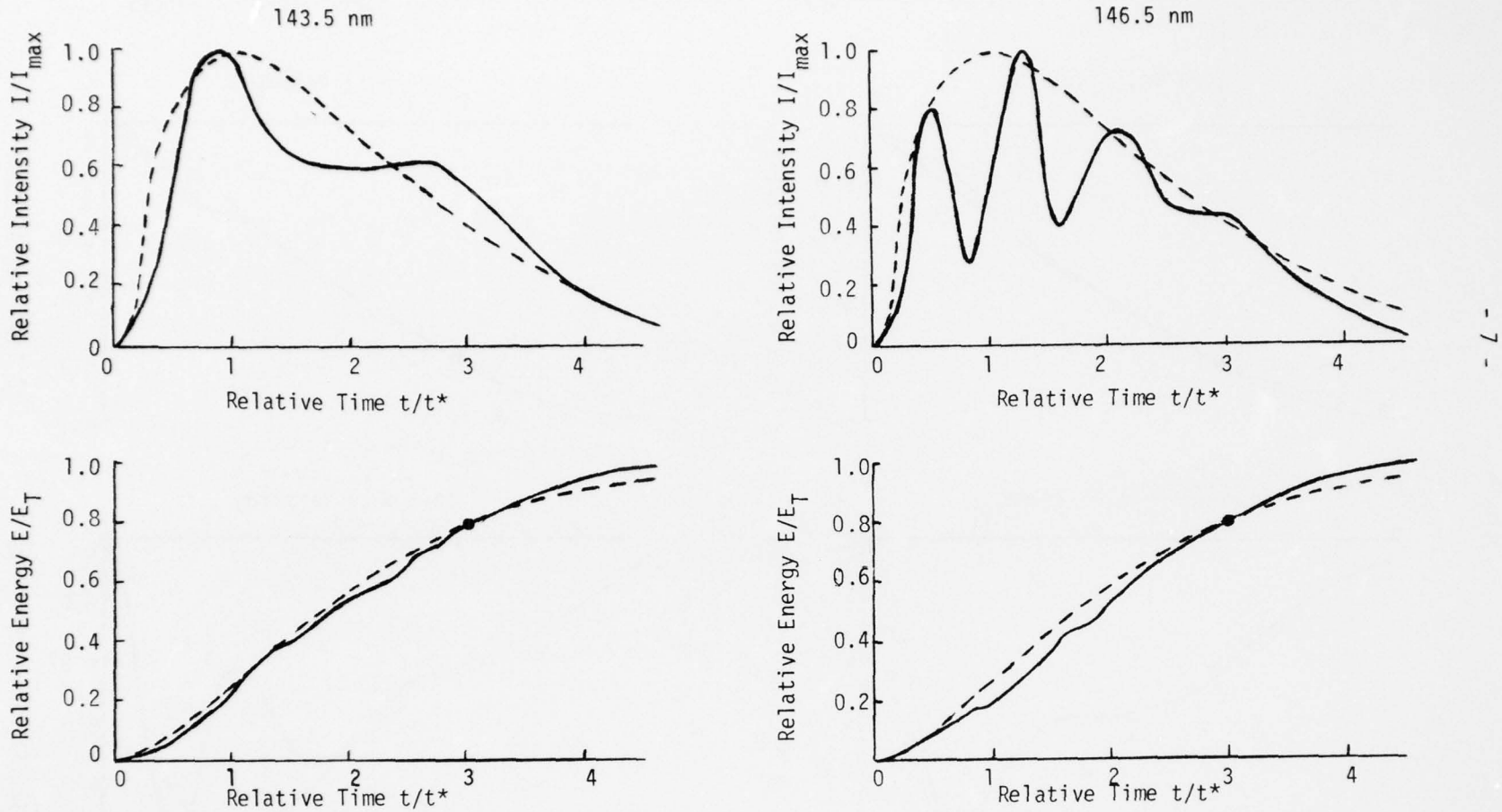


Figure 3 - Relative Values of Intensity and Energy vs Time for Pulsed VUV Light Source: Experimental (Solid Curve), Critically Damped Representation (Dashed Curve)

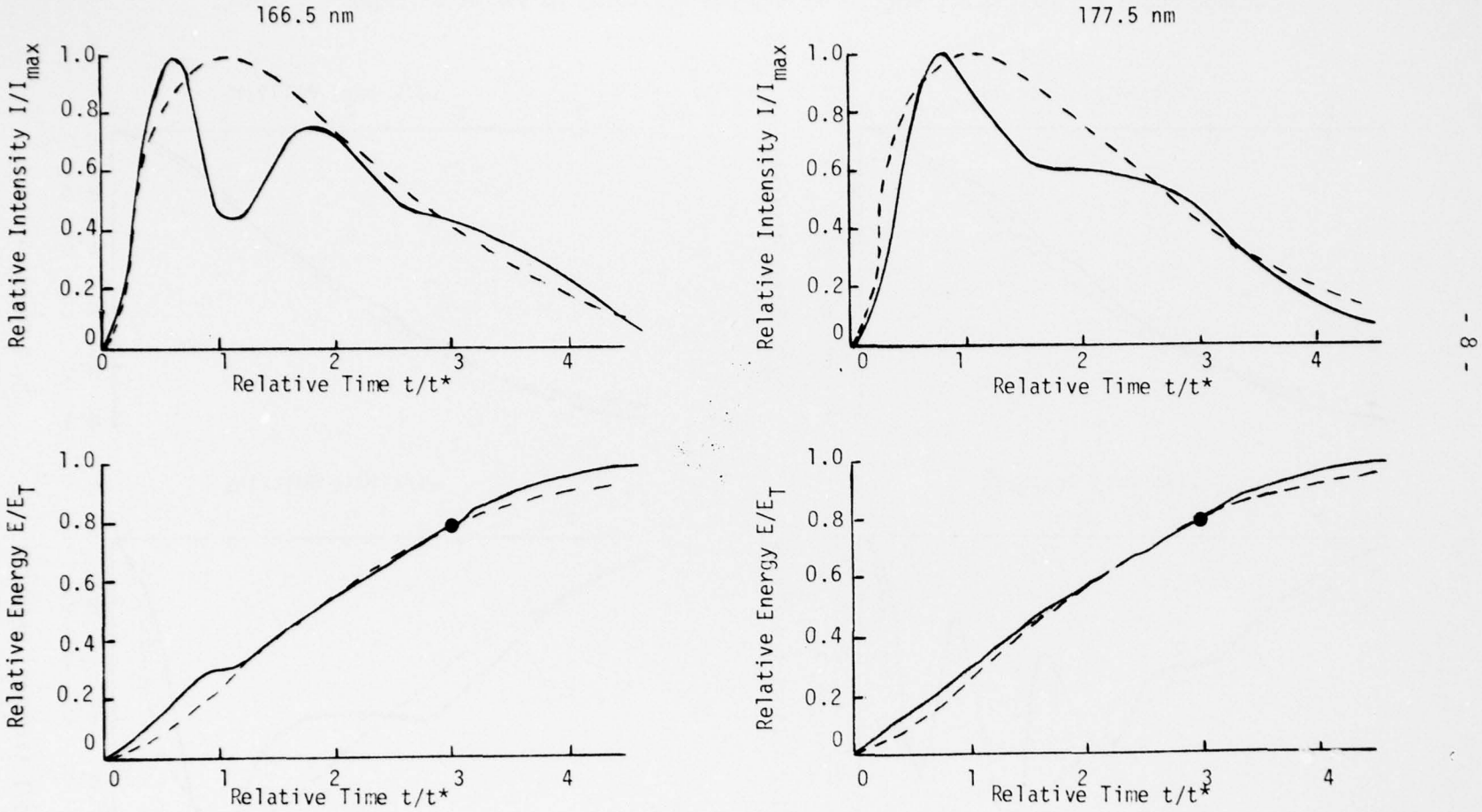


Figure 3 (Continued) - Relative Values of Intensity and Energy vs Time for Pulsed VUV Light Source: Experimental (Solid Curve), Critically Damped Representation (Dashed Curve)

the present point light sources after penetration of various fuel-free air layers is shown in Figure 4. For comparison, the corresponding requirements for parallel and focused beams are also illustrated. The curve for the point source represents the effect of energy loss due to beam spreading and oxygen absorption while the curves for parallel and focused beams represent oxygen absorption only. A concentrating factor of 10 was assumed for the focused beam. Allowing an energy increase by a factor of 10 (hydrogen-oxygen ignition would now require 5J of input energy) would permit air layers of about 0.15 cm (0.060 in) to be penetrated. This distance can be extended to about 0.40 cm (0.157 in) by using a parallel beam and about 2.1 cm (0.83 in) by using a focused beam. Application of the radiative ignition technique where fuel-free air boundary layers are present would benefit substantially by the development of parallel beam and particularly focused beam VUV sources. Alternate approaches would involve increasing stored energy to photon-flux conversion efficiency of the present source, developing a means of rapidly mixing oxygen atoms generated in the boundary layer with fuel species, or removing the presence of the boundary layer in the vicinity of the light source. Maximum flexibility would be retained by following the light source development approach.

Propane-air ignition tests are currently in progress. Minimum ignition energy is found to be on the order of 4 J for propane concentrations of about 4% (stoichiometric) at 66.6 kPa (500 torr) pressure. This represents an increase of only about a factor of 4 over hydrogen-air radiative ignition requirements. For spark ignition, the corresponding factor for hydrogen-air vs hydrogen-oxygen ignition is 14. Propane-air tests will also be conducted to 101 kPa (1 atmosphere) to provide base-line data at zero velocity for comparison with results at reactant flow conditions.

(Task d) Radiative Initiation Model

The modeling effort on radiative initiation of hydrogen-oxygen-nitrogen mixtures has progressed. Based on the model results, a new mechanism for radiative enhancement of combustion has been formulated. The mechanism involves the influence of photon generated oxygen atoms on combustion reaction kinetics wherein the realization of reduced reaction time results in enhanced flame propagation. Attachment II is an expanded abstract of a Combustion Institute paper which presents further details on the modified enhancement mechanism, the modeling approach taken, and some initial modeling results.

Other model results indicate a beneficial effect of moisture on the ignition process and the existence of an optimum pulse period for ignition. The improvement in ignitability by the addition of moisture to the reactant mixture has been verified experimentally as indicated by results described in the following section. It appears that water vapor acts as a sensitizer by participating in photon absorption and then dissociating into hydroxyl and hydrogen radicals. Optimum pulse periods were calculated to be on the order of 10 to 20 μs for radiative ignition. Although experimental pulse periods this short have not been used, a trend of decreased ignition energy with decreasing pulse duration in the range 320 to 60 μs agrees with this result (2). A long radiant pulse is undesirable since a buildup of high oxygen atom concentrations is prevented by loss mechanisms

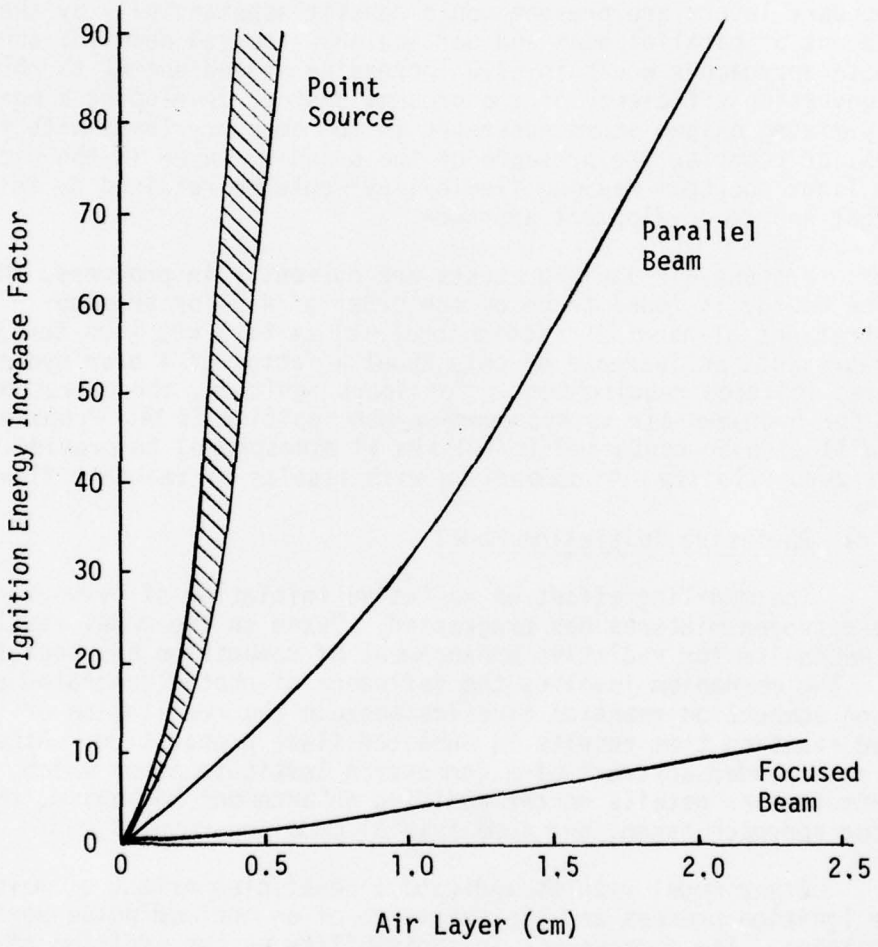


Figure 4 - Estimated Energy Increase Required to Achieve Radiative Ignition After Penetration of an Air Layer at 800 K and 101.3 kPa

such as atom recombination or ozone formation. However, it appears desirable to save some of the photon energy which results in dissociation until the reactant mixture temperature increases to the point where more rapid use of constructive oxygen atom reactions result. Consequently, very short pulses should also be avoided.

(Task e) Source/Combustion Diagnostics - II

A focused EIMAC light source has been used to irradiate hydrogen-oxygen and methane-oxygen mixtures. Continuous irradiation at the 500 watt level and pulsed operation up to 50 Joules has been employed. Steady irradiation with this source appears to be incapable of initiating sustained reactions but does result in the formation of a small amount of water vapor. Sporadic ignitions were observed only when the continuous irradiation starting transient (brief power level greater than 500 watts) or the pulsed operating mode is allowed to interact with a mixture containing water vapor. The enhancing effect of water vapor has been verified by our computer model.

The formation of water vapor under continuous irradiation indicates that the light source capability is probably within a factor of 10 of being able to ignite reactant systems. Improvement of the present optical arrangement and the use of better grade sapphire windows would be positive factors in developing continuous radiative ignition systems.

REFERENCES

(1) Cerkanowicz, A. E., and Bartok, W., "Radiation Augmented Combustion", Interim Report AFOSR-TR-78-1508, July 1978.

(2) Cerkanowicz, A. E., "Photochemical Enhancement of Combustion and Mixing in Supersonic Flows", Interim Report AFOSR-JR-73-0563, March 1972.

PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT

Dr. A. E. Cerkanowicz - Principal Investigator - PhD Thermodynamics, Stevens Institute of Technology, 1970.

Dr. W. Bartok - Combustion Consultant and Group Head - PhD Physical Chemistry, McGill University, 1957.

Dr. W. S. Blazowski - Combustion Consultant and Group Leader - PhD Mechanical Engineering, Stevens Institute of Technology, 1971.

Dr. J. Stevens - Mathematics Consultant - PhD Courant Institute of Mathematic Sciences, New York University, 1972.

Mr. C. Ward - Experimentalist (summer) - B.S. Chemical Engineering, Princeton University, 1979.

Dr. J. Shaw - Light Source Design and Development (ILC) - PhD Mechanical Engineering, Stanford University, 1968.

INTERACTIONS/OUTSIDE INTEREST

A. Talks and Papers

A paper entitled "Radiative Augmentation of Combustion: Modeling" was presented at the Eastern States Section Combustion Institute meeting on Chemical and Physical Processes in Combustion on November 28-29 and December 1, 1978.

Presentations were given at the following AFOSR Contractors Meetings: "Mechanisms of Radiation Augmented Ignition and Combustion", Air-Breathing Combustion Dynamics and Kinetics, Dayton, Ohio, October 1978; "Radiative Augmentation of Combustion", Meeting and Workshop on Unconfined Detonations and Other Explosion Related Research, Fort Walton Beach (Eglin AFB), Florida, January 1979.

A paper entitled "Case Studies in the Simulation of Novel Combustion Techniques" has been accepted for presentation at the 1979 Summer Computer Simulation Conference, July 16-18, 1979, Toronto, Canada.

B. Interest Expressed by Other Scientists

Much of the work of Professor F. Weinberg at Imperial College, London, relates to various combustion augmentation approaches. Professor Weinberg has carried out experiments on augmentation using plasma torch devices and is interested in the potential radiative effect of these devices. Conversely, we are interested in the potential thermal and excited species effects of the plasma torch as additional augmentation factors for unconfined light source plasmas. Open communication has been established with this group.

John Manheim of Wright-Patterson Air Force Base has expressed interest in our computer model of photochemical combustion effects. Their studies of laser ignition of aircraft fires could benefit substantially by the model we have developed under AFOSR contract. We indicated that our immediate effort does not provide the necessary documentation of the program to allow for its use by others. Documentation is part of our program effort that would be undertaken during the final reporting procedure.

Contact has been made with Don Brunda and Bill Wagner of the Naval Aeropropulsion Center, Trenton, New Jersey. They have been following our work in the radiative ignition area and have been approached by ILC to fund a small program involving photochemical ignition of jet fuel.

Request for additional information on the radiative ignition work has also been received from the following professionals: Mr. Marvin Smith, Independent Consultant, Muncie, Indiana; Dr. Francis E. Fendell, TRW, Redondo Beach, California; and Pro. J. M. Calo, Princeton University, Princeton, New Jersey.

POTENTIAL APPLICATION OF RESEARCH RESULTS

The work in progress on radiative initiation and augmentation of combustion is providing fundamental information on a unique combustion process. Concepts which represent a new departure and extension of conventional combustion practice can evolve from the data being obtained. Aspects of the radiative ignition and enhancement concept have been utilized in demonstrating new approaches for initiating fuel-air explosions* and for improving automotive engine efficiency.** Eventual application to gas turbine engine systems is envisioned both for improved combustor initiation and flame holding. To this end, continued VUV light source development in the direction of improved beam optics (parallel and focused beams) is desirable. High altitude combustor re-ignition following flame-out, drag-free flame stabilization in supersonic combustors, and added flexibility for conventional combustors to use future alternate fuels represent some future areas of potential application.

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* Work in progress by J. Lee at McGill University, Montreal, Canada.

** Work in progress by Rigs Corporation, North Chelmsford, Massachusetts.

ATTACHMENT I

ILC Technology

R-ILC-79-9

UV COMBUSTOR LIGHT SOURCE DEVELOPMENT

FINAL REPORT

June 1979

Prepared for: Exxon Research and Engineering Company
Government Research Laboratory
Advanced Energy Systems Laboratory
P.O. Box 8
Linden, New Jersey 07036

Prepared by: J. F. Shaw

Approved by: _____
Dr. Leonard Reed, Vice President, Engineering

399 Java Drive ☐ Sunnyvale, California 94086 ☐ Phone 408/745-7900 ☐ TWX 910-339-9389

INTRODUCTION

From January 1978 to December 1978, ILC Technology was involved in developing pulsed UV igniter sources for Exxon. The primary goal of the development effort was to produce a source with high vacuum ultraviolet (VUV) output that was stable over thousands of shots. This primary goal was achieved, and ten sources plus a power supply were delivered at the end of the program. Significant problems in source development still remain, however, and new source development effort should be considered for use in any flowing mixture test program.

INITIAL SOURCE DESIGN

The initial design was intended to model the earlier Photochem Industries igniters that had demonstrated good efficiency but erratic performance. As a result, an axially symmetric design was chosen with a conventional cathode and ring anode.

In the interest of lessening development time, a demountable structure based on commercially available conflat vacuum flanges, high voltage feedthroughs, and sapphire viewing ports, was configured for initial tests. This design, in theory, provides stock parts and a flexible mounting structure. Spacing from cathode tip to window was chosen to be variable between .125 and .062 in., and a long tubulation was used to allow multiple runs at various pressures. The initial source used a .062 in. gap and a 2 atm fill pressure of xenon. To ensure long life, the unit was baked out at 400°C for an hour.

In practice there was a two month delay in obtaining these "stock" parts, and when finally assembled, it proved impossible to ignite the H_2-O_2 test mixture. Input energy to the source was slowly increased to 50 J per pulse with no result. A pulsewidth 20 μsec and a peak current of 1600 A was measured but no ignition occurred.

A different electrical configuration was tried, and the system was run at the same peak current but with a much shorter 2 μsec pulse. This had no effect on the combustible mixture but produced visible degradation of the source window.

At this point it was decided to test the vendor supplied window for VUV transmission. The lab report showed that the window was not VUV grade with less than 10 percent transmission at 160 nm and in fact was less transmissive than typical curves for normal sapphire. This explained the lack of success in source development but did not indicate the best solution to the problem. After writing an appropriate letter to the vendor sales department, this approach was abandoned.

FINAL SOURCE DESIGN

Figure 1 shows the more conventional brazed assembly used for the final design. Electrode placement and spacing was similar to that of the initial design but a fixed geometry was used along with a hard seal copper braze of the sapphire and alumina to the Kovar end members. The windows were obtained from Insaco and transmission tested before use. This source was filled to 150 psia xenon and then run. Ignition occurred at 2.0 J in the first test series.

Subsequent testing showed threshold ignition energy to be fairly repeatable as shown in Table 1. A maximum threshold energy of 1.20 J was shown by the first source after life testing for 10^4 shots. The minimum ignition energy shown was 0.72 J. There was some indication that this minimum energy was the minimum trigger level for the electrical system and not the energy minimum for the light source. It is possible that a lower capacitance system operating at a higher voltage would show a lower threshold energy.

This level of 0.8 J compares to the reported minimum value of 0.25 J for a few units of older design. Some of this is explainable due to the thicker sapphire window material and

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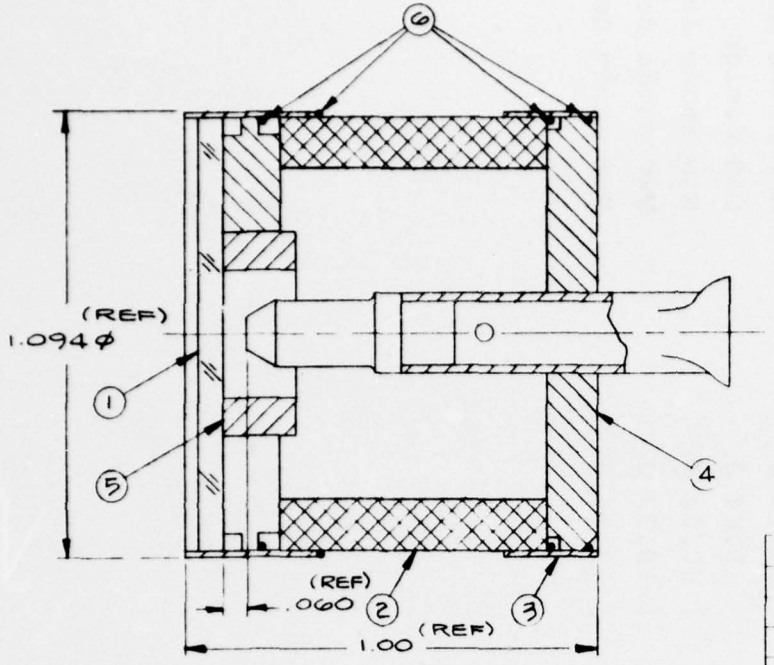

NOTES:

1. FINAL ASSY TO BE LEAK TIGHT TO 1×10^{-9} Pa·m²/SEC He

ITEM NO.	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION
6	A/R			BRAZING WIRE, CUSIL
5	1		33220	ANODE ASSY.
4	1		33232	CATHODE ASSY.
3	1		33222-002	SLEEVE
2	1		33231	INSULATOR, METALLIZED
1	1		33252	WINDOW ASSY.

PARTS LIST

NEXT ASSY	USED ON
	33230

APPLICATION

UNLESS OTHERWISE SPEC DIMENSIONS ARE IN INCHES
TOLERANCES
FRACTIONS ±
ANGLES ±
.XX DEC ±
.XXX DEC ±

MATERIAL: SEE P/L

FINISH:

DIMENSIONING AND TOLERANCING PER USASI Y-14.5

DRAWN N.S. Beatty DATE 9-18-78
CHECK
APPD R. MINER 9/18/78
DESIGN ACTIVITY APPD

ILC Technology, Inc.
399 Java Drive, Sunnyvale, Calif 94086

TITLE: UV COMBUSTOR ASSY.

SIZE	CODE IDENT. NO.	DWG. NO.	
B	31573	33230	A

SCALE 4X | SHEET 1 OF 1

TABLE 1. Threshold Ignition Energy

(C = 100 μF, H_2-O_2 at 0.5 atm, all units have 20 shots at 10 J for burnin)

Combustor No.	Threshold Energy	Remarks
1	1.20 J	After life test
2	0.72 J	New anode design
3	0.98 J	New anode design
4	0.72 J	New anode design
5	0.72 J	New anode design
6	0.72 J	New anode design
7	0.84 J	Old design
8	0.72 J	New anode design
9	0.72 J	New anode design
10	0.84 J	New anode design

the non-optimum transmission of the Insaco sapphire. Still, a threshold energy of 0.4 J would be expected based on these source characteristics. This factor of two difference is probably due to the driving circuit used in this application.

A 100 μF capacitor running at 120 V was used to drive the lamp. An ILC T-195B commercial trigger transformer with a peak output voltage of 20 kV was used to initiate the discharge. A ringing discharge was observed at high energies and, even at lower energies, it is unlikely that all the capacitor energy was delivered to the light source. It is likely that fine tuning the driving circuit would lower the threshold energy to 0.4 J.

LIFE TEST RESULTS

Two sources were life tested to confirm stable output over a large number of shots. Source number 1 was run at steadily increasing energy levels up to 20 J per pulse. The source accumulated 10^4 shots at 2.5, 4.5, and 10.1 J per pulse and 5000 shots at 20 J per pulse. There was no visible degradation and the test was stopped due to failure of the trigger transformer rather than source problems. Source number 2 was life tested to 10^4 shots at 20 J and its ignition energy was checked and found to be 1.6 J. While this was higher than its initial threshold energy, it was felt that this was a reflection of a higher trigger level than a decrease in radiometric efficiency. Therefore, this source design appears to have the desired characteristic of providing stable radiometric output over a large number of shots.

The misflash probability increased markedly during both life tests. This is the probability of a normal trigger pulse reaching the lamp and no discharge occurring. Initially the misflash probability was about 5% for operation at the 20 J level but rose to about 20% during the life test. At moderate energies the level rose to about 50% and the source refused to

trigger at all at low levels. This behavior is typical of short arc sources and is due to slow erosion of the cathode tip by arc action. This removes any sharp corners and lowers the local electrical field which in turn requires a higher trigger voltage for ignition. While not considered in the initial design criteria, trigger voltages above 20 kV start to cause real hardware problems. It may be the case that the rise of trigger voltage with lifetime forms a practical upper limit on source life. Future source designs should take this into account and attempt to limit the trigger voltage to 15 kV even at some loss in source efficiency.

ELECTRICAL PERFORMANCE

Devices run in acceptance test were operated at bank voltages between 120 V and 650 V. At 650 V a peak current of 800 A was observed with a 120 μsec pulsewidth, and at low energies the comparable values were 240 A and 160 μsec. Initially the trigger voltage would break down across the insulating ceramic. This problem was cured by wrapping the anode end in Teflon tape and increasing the breakdown path length. In the future the insulator path length should be increased by about 0.5 in.

As mentioned previously, trigger voltage started at about 12 kV and increased with life to roughly 18 kV. This was the voltage required to trigger the first pulse of a series and after an initial pulse, the self heating of the cathode was sufficient to lower the trigger voltage for subsequent pulses. In observing extended operating times at marginal trigger voltages, this led to a sequence of several flashes (as many as 20) followed by a comparable number of misses. Triggering voltage can be reduced by lowering the gas pressure, shortening the arc gap or using more pointed electrodes. Unfortunately, lowering gas pressure decreases conversion efficiency, shortening the arc gap has a weak effect on trigger voltage, and using a pointed electrode leads to quick erosion and short lamp life. It should still be possible to make some minor changes and get a trigger voltage that will stay below 15 kV.

CONCLUSIONS

The UV combustor devices produced in this program have fulfilled the basic requirement for a long life source with stable UV output. Tests at ILC indicate a life of at least 10^4 shots with 20 J input. Further, they appear to be operable over the desired 100 to 1 dynamic range. Tests at ILC have shown operation from 0.7 to 20 J and the devices have been run at 50 J by Exxon. In this respect the development effort has been completely successful.

Operating experience has shown several deficiencies which should be corrected when more units are built. First, the UV windows used in the current units have satisfactory, but not good, VUV transmission. Second, the ceramic insulator cylinder is not long enough and should be lengthened. Third, external metal parts should be modified to provide a convenient means of pressure sealing the device to a test chamber and to provide electrical connections for both anode and cathode. These changes can be made in a straightforward manner. Also the lamp trigger voltage should be decreased and the unsaturated inductance of the pulse transformer decreased. These changes can also be made relatively easily.

Two fundamental characteristics of this design are not so easily changed, however. Because of the large cylindrical anode, the arc never fills the gap completely and as a result changes its angular position with each energy pulse. This is not a serious problem in a combustor, but it makes it very difficult to align the source with an optical system and take precise radiometric data. A more conventional anode much smaller with respect to the discharge volume is required. Second, the polar distribution of UV light output from the source appears to be generated by a point source just off the cathode tip, i.e., the cathode spot. This divergent beam has the undesirable characteristic of decreasing its intensity with distance from the source. In certain cases as with a fuel free

boundary layer ignition must occur as much as 0.5 in. from the source and at this point output from the present source design will have dropped nearly an order of magnitude.

In summary, the basic source design developed for UV combustors has met its basic design goals of repeatable radiometric performance, large dynamic range, and long life. Operating experience has shown several minor problems which should be corrected the next time units are built. Overcoming the two fundamental problems of this source, a wandering arc spot and a divergent output beam, will require development of a totally different source design in a new program.

ATTACHMENT II

RADIATIVE AUGMENTATION OF COMBUSTION
CONTRACT F49620-77-C-0085

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Combustion systems are limited by combustion associated phenomena such as flammability, flame propagation, ignition, and stable combustion. An insufficient understanding is available of the basic mechanisms and processes associated with promising techniques for enhancement of combustion and of combustion initiation. As part of our Air Force sponsored program, radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediate species is being investigated. Pulsed vacuum ultraviolet (VUV) and continuous ultraviolet (UV) light sources are being used for this purpose. Experimental efforts are being directed at elucidation of spectral characteristics and reactant mixture-photon interactions. Preliminary results of a complementary effort modeling photochemical initiation and enhancement of combustion are the subject of this presentation.

The concept of radiative initiation and enhancement of combustion can be characterized by reference to a phase plane diagram (1) as illustrated in Figure 1. For a reactant mixture, this diagram presents the temperature versus oxygen atom concentration plane which results from a solution of the combined energy and species conservation equations.+ Time is an implicit parameter for all curves. Two regions are shown separated by line C_1-C_2. The lower region is a stable or noncombusting region while the upper region is one of rapid reaction (combustion). Before combustion is initiated the reactant mixture will be at a stable or nodal point. Thermal ignition involves imposing a temperature rise such that the thermodynamic state of the mixture moves into the rapid reaction region. Ideally, photochemical initiation need not involve a temperature rise. It is achieved by increasing the concentration of an important reaction intermediate, in this case oxygen atoms, and moves the thermodynamic state of the mixture into the rapid reaction region via photodissociation. The photochemical path results in completely different ignition characteristics than the thermal path. Photochemical enhancement results at mixture locations where oxygen atom concentrations in the range S-C_2 are achieved. At these concentrations, a temperature rise essentially equivalent to that required for thermal ignition is still needed to move the mixture thermodynamic state into the combustion region. However, the resulting combustion region reaction paths (e.g. S-N_2) entail different reaction times for the establishment of flame conditions. Higher initial oxygen atom concentrations result in reduced kinetic time in the combustion region and consequently the realization of enhanced flame propagation. An alternate combustion enhancement approach involves irradiating the mixture during the combustion process to favorably alter the reaction kinetics by photodissociation of combustion intermediate species involved in degenerate chain branching steps (2).

+ A multi-dimensional space representation of temperature and reactant intermediary species concentration should be used to portray real combustion system characteristics. However, oxygen atom concentration provides a satisfactory surrogate representation of the general behavior of the intermediate species.

A comprehensive model of radiative initiation and enhancement of hydrogen-oxygen-nitrogen mixtures is being developed. The model includes the effect of light source characteristics; photodissociation of light absorbing species, reactant mixture kinetics, including electronically excited state species; and adiabatic temperature rise due to reaction heat release. The species considered in the radiative initiation and enhancement model for the H_2-O_2-N_2 system are listed in Table 1. A literature review was undertaken and best values for the rate constants in the form AT^{-B} exp (-C/T) for reactions involving these species were obtained. The current version of the model considers approximately ninety such reactions. The minimal set required and a sensitivity analysis of the rate data for those dominant reactions is under investigation.

Radiant absorption by reactant and combustion-intermediate species is considered to follow a Beer-Lambert Law. The dissociation products formed, which may include excited states, are dependent on the energy of the photon absorbed. The photodissociation reactions which can occur are also listed in Table 1.

For a given absorbing species dissociating to specified products, the unimolecular photochemical reaction rate constant is given by the following equation.

$$k(x,t) = \int_0^\infty I(x,t,\lambda)T(\lambda)\phi(\lambda)[\lambda/hc]\sigma(\lambda)\exp\left[-\sum_{i=1}^{N}\sigma_i(\lambda)\int_0^x n_i(x,t)dx\right]d\lambda$$

where:
- t = time
- x = distance from light source window
- λ = wavelength
- n_i = concentration of light absorbing species
- σ_i = absorption cross-section of light absorbing species
- ϕ = quantum yield of dissociation
- T = window transmission
- I = source irradiance

Quite general light source characteristics can be considered in the specification of the source irradiance. Intensity is considered to be dependent on wavelength, time, input energy, and optical arrangement (i.e. parallel beam, focused beam, point source). As well, the transmission characteristics of window material such as quartz or sapphire can be incorporated by specification of window transmission. Absorption coefficients for all light absorbing species are tabulated, and the treatment of molecular oxygen absorption in the Schumann-Runge bands follows that given by G. Kockarts (3). In the current implementation of the model, all absorbing species are reckoned to dissociate with the rate constant calculated from the cited equation, but the attenuation of light intensity by the mixture is taken to be due solely to O_2. This assumption is reasonable, even in wavelength regions in which O_2 does not absorb strongly, due to the low column density of the other absorbers during the irradiation period.

The final model equations are thus the collection of rates of change in species concentrations due to reaction and photodissociation, together with an adiabatic heat balance. Future plans call for the inclusion of diffusion, heat loss, and wall recombination effects as well as consideration of methane fueled systems. The resulting nonlinear system of differential equations was solved to high-order accuracy using the stiffly stable multistep method of Gear (4). An equation-writer code received from Los Alamos Scientific Laboratory was modified to aid in the generation of the code required to describe the chemical kinetic effects of a large number of reactions on the individual species balance equations (5). The program also produces code to calculate the Jacobian of the system.

Figure 2 illustrates model predictions for the irradiation of a 298 K, 40 kPa, hydrogen-oxygen mixture. Each curve represents a photochemical path (time implicit) in the phase plane for a given radiant intensity. The radiant pulse was assumed to be a critically damped discharge with a time to peak intensity of 20μs. For low radiant intensities (50, 75, 80) the radiant pulse generates oxygen atoms and some temperature rise, but the final tendency of the mixture is to return to the initial conditions that existed before irradiation. This fact is indicated by the flattening out of the temperature profile, and the failure to achieve combustion within a characteristic heat loss period because no heat loss is currently accounted for in the model. At higher radiant intensities (85, 90, 100), the irradiated mixture has entered the unstable zone and the tendency to return to the initial conditions is overcome. All of these high intensity conditions eventually result in rapid burning (combustion). These results indicate that a critical radiant intensity exists below which ignition is not achieved, in agreement with earlier experimental results (1). The nature and character of the curves are compatible with the combustion system behavior indicated by a general phase plane analysis.

The inclusion of electronically excited state species favorably alters the kinetics resulting in improved combustion behavior. Both intensity and time to achieve rapid reactions are reduced by the presence of excited state species. When the model is altered so that only ground states are reckoned to be produced by photodissociation, thus effectively eliminating all excited state kinetics, the radiant energy needed to achieve combustion is approximately twice that required with the inclusion of excited states. Thus, it is clear that excited state species and their reactions must be included in the modeling of photochemical initiation and enhancement of combustion. Optimization of the spectral distribution of light source radiation is also shown to be an important consideration. Radiation in the spectral region from 145-165 nm is critical for reaction initiation while initiation kernal growth is influenced by 145-180 nm radiation. Enhancement of flame propagation is brought about by radiant energy in the 165-200 nm range. The existence of an optimum pulse period for effective coupling of the radiant input energy to the kinetic reactions for combustion initiation is also indicated.

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FIGURE 1
PHASE PLANE DIAGRAM FOR AN
ADIABATIC HYDROGEN-OXYGEN COMBUSTION SYSTEM

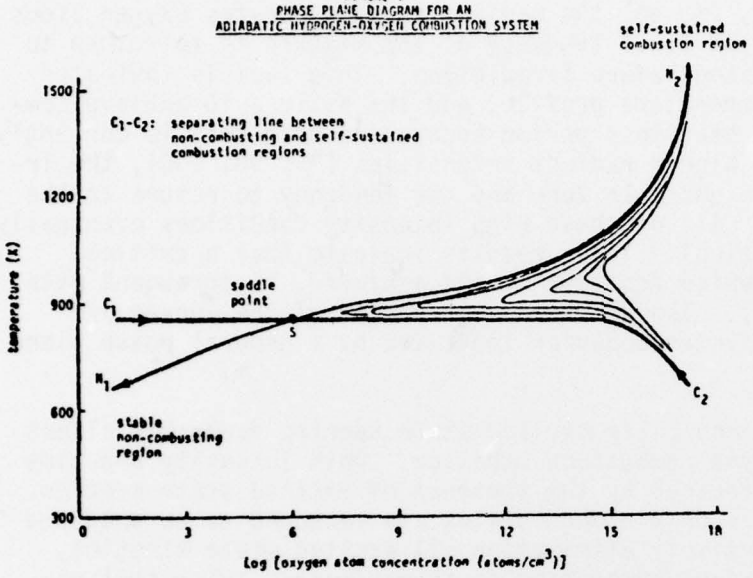

TABLE 1
HYDROGEN-OXYGEN PHOTOCHEMICAL SYSTEM

REACTANT SPECIES

$O(^1D)$	O_2	OH
O	O_3	H_2O
$O_2(^1\Sigma_g^+)$	H	HO_2
$O_2(^1\Delta_g)$	H_2	H_2O_2

PHOTODISSOCIATION REACTIONS

O_2	+ $h\nu$ (λ < 245)	→ O	+ O
O_2	+ $h\nu$ (λ < 175)	→ O	+ $O(^1D)$
O_3	+ $h\nu$ (λ < 1140)	→ O_2	+ O
O_3	+ $h\nu$ (λ < 310)	→ $O_2(^1\Delta_g)$	+ $O(^1D)$
O_3	+ $h\nu$ (λ < 260)	→ $O_2(^1\Sigma_g^+)$	+ $O(^1D)$
H_2O	+ $h\nu$ (λ < 242)	→ OH	+ H
HO_2	+ $h\nu$ (λ < 456)	→ OH	+ O
H_2O_2	+ $h\nu$ (λ < 365)	→ OH	+ OH

FIGURE 2
REACTANT MIXTURE PHASE PLANE PATHS
DURING PULSED VACUUM ULTRAVIOLET IRRADIATION